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Is there New Physics in B Decays ?

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Abstract

Rare decays of the B meson are sensitive to new physics effects. Several experimental results on these decays have been difficult to understand within the standard model (SM) though more precise measurements and a better understanding of SM theory predictions are needed before any firm conclusions can be drawn. In this talk we try to understand the present data assuming the presence of new physics. We find that the data points to new physics of an extended Higgs sector and we present a two higgs doublet model with a 2-3 flavor symmetry in the down type quark sector that can explain the deviations from standard model reported in several rare B decays.

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1 Introduction

Experiments at B factories have demonstrated that the CKM matrix is the dominant source of CP violation in hadronic processes specially in decays dominated by tree amplitudes. These experiments have also confirmed that CP violation in the standard model(SM) is large. Now, it is widely expected that new physics (NP) necessary to stabilize the standard model Higgs mass and provide an explanation for electroweak symmetry breaking will be revealed around $\sim \text{TeV}$. As CP violation is not a symmetry or an approximate symmetry of nature it is natural to expect this NP to be associated with new CP violating phases which may be large and could be observable in B decays.

Rare B decays, where penguin amplitudes play a dominant role, are excellent places to look for new physics CP violating effects [1]. Decays that go through $b \rightarrow s$

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transitions are specially interesting as the SM predictions for CP violation in several of these decays are tiny, making them ideal places to look for new physics CP odd phases. It is therefore of crucial importance to test the SM picture of CP violation in these decays.

In fact there are already many measurements in rare B decays. Interestingly, quite a few of these measurements have been difficult to understand within the SM. First, within the SM, the measurement of the CP phase $\sin 2\beta$ in $B_d^0(t) \rightarrow J/\psi K_s$ should be approximately equal to that in decays dominated by the quark-level penguin transition $b \rightarrow sq\bar{q}$ ($q = u, d, s$) like $B_d^0(t) \rightarrow \phi K_s$, $B_d^0(t) \rightarrow \eta' K_s$, $B_d^0(t) \rightarrow \pi^0 K^0$, etc. However, there is a difference between the measurements of $\sin 2\beta$ in the $b \rightarrow s$ penguin dominated modes ($\sin 2\beta = 0.50 \pm 0.06$) and that in $B_d^0(t) \rightarrow J/\psi K_s$ ($\sin 2\beta = 0.685 \pm 0.032$) [2, 3, 4]. Note that the $\sin 2\beta$ number for the $b \rightarrow s$ penguin dominated modes is the average of several modes. The effect of new physics can be different for different final hadronic states and so the individual $\sin 2\beta$ measurements for the different modes are important. Second, the latest data on $B \rightarrow \pi K$ decays (branching ratios and various CP asymmetries) appear to be inconsistent with the SM [5, 6, 7].² Third, within the SM, one expects no triple-product asymmetries in $B \rightarrow \phi K^*$ [9], but BaBar has measured such an effect at 1.7σ level [10]. There are also polarization anomalies where the decays $B_d^0 \rightarrow \phi K^*$ and $B^+ \rightarrow \rho^+ K^*$ appear to have large transverse polarization amplitudes in conflict with naive SM expectations [4, 11, 12].

While these deviations certainly do not unambiguously signal new physics, they give reason to speculate about NP explanations of the experimental data. Furthermore, it is far more compelling to find NP scenarios that provide a single solution to all the deviations than to look for solutions to individual discrepancies. Taking all these deviations seriously one is lead to certain structures of NP operators that can explain the present data[13]. The structure of these operators, which involve scalar-pseudoscalar currents, strongly suggest NP associated with an extended Higgs sector. One of the simplest options is to consider a 2 Higgs doublet model that generates new flavor changing neutral current (FCNC) effects of the right strength. The model that we will consider will generate new FCNC effects at the tree level. It is known that FCNC $b \rightarrow s$ transitions in the SM are not only loop suppressed but are also suppressed by small mixing angles. Hence to produce effects of the right order (or the same size as the SM FCNC amplitudes) FCNC effects in the NP model must receive additional suppression on top of the suppression due to the mass of the heavy scalar (or pseudoscalar) exchange which we take to be around a TeV. The choice for the heavy scalar(pseudoscalar) mass, m_H , is based on the assumption that the same new physics needed for the Higgs mass stabilization is also responsible for new FCNC effects in B decays. This additional suppression, which is given by m_s/m_b in our model, comes from the breaking of a 2-3 flavor symmetry by the strange quark

² A cleaner test of the SM could be provided by looking at the quasi-exclusive decays $B \rightarrow KX$ [8] rather than the exclusive $B \rightarrow K\pi$ decays.

mass [14, 15]. We now give details of the two Higgs doublet model in the following section.

2 A Specific NP Model

Our model of NP is a two Higgs doublet model which has a 2-3 interchange flavor symmetry in the down quark sector like the $\mu - \tau$ interchange symmetry in the leptonic sector [14, 15]. The 2-3 symmetry is assumed in the gauge basis where the mass matrix has off diagonal terms and is fully 2-3 symmetric. Diagonalizing the mass matrix splits the masses of s and b or μ and τ and leads to vanishing $m_s(m_\mu)$. The breaking of the 2-3 symmetry is then introduced through the strange quark mass in the quark sector and the muon mass in the leptonic sector. The breaking of the 2-3 symmetry leads to flavor changing neutral currents (FCNC) in the quark sector and the charged lepton sector that are suppressed by $\frac{m_s}{m_b}$ and $\frac{m_\mu}{m_\tau}$ in addition to the mass of the Higgs boson of the second Higgs doublet. Additional FCNC effects of similar size can be generated from the breaking of the $s - b$ symmetry in the Yukawa coupling of the second Higgs doublet. In what follows we will limit our discussions only to the quark sector.

We consider a Lagrangian of the form,

$$\mathcal{L}_Y^Q = Y_{ij}^U \bar{Q}_{i,L} \tilde{\phi}_1 U_{j,R} + Y_{ij}^D \bar{Q}_{i,L} \phi_1 D_{j,R} + S_{ij}^U \bar{Q}_{i,L} \tilde{\phi}_2 U_{j,R} + S_{ij}^D \bar{Q}_{i,L} \phi_2 D_{j,R} + h.c., \quad (1)$$

where ϕ_i , for $i = 1, 2$, are the two scalar doublets of a 2HDM, while $Y_{ij}^{U,D}$ and $S_{ij}^{U,D}$ are the non-diagonal matrices of the Yukawa couplings. After diagonalizing the Y matrix one can have FCNC couplings associated with the S matrix.

For convenience we express ϕ_1 and ϕ_2 in a suitable basis such that only the $Y_{ij}^{U,D}$ couplings generate the fermion masses. In such a basis one can write,

$$\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad \langle \phi_2 \rangle = 0. \quad (2)$$

The two Higgs doublets in this case are of the form,

$$\begin{aligned} \phi_1 &= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H^0 \end{pmatrix} + \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\chi^+ \\ i\chi^0 \end{pmatrix}, \\ \phi_2 &= \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}H^+ \\ H^1 + iH^2 \end{pmatrix}. \end{aligned} \quad (3)$$

In principle there can be mixing among the neutral Higgs but here we neglect such mixing. We assume the doublet ϕ_1 corresponds to the scalar doublet of the SM and H^0 to the SM Higgs field. In addition, we assume that the second Higgs doublet does not couple to the up-type quarks ($S^U \equiv 0$). For the down type couplings in Eq. 1 we have,

$$\mathcal{L}_Y^D = Y_{ij}^D \bar{Q}_{i,L} \phi_1 D_{j,R} + S_{ij}^D \bar{Q}_{i,L} \phi_2 D_{j,R} + h.c. \quad (4)$$

We assume the following symmetries for the matrices Y^D and S^D :

- There is a discrete symmetry under which $d_{L,R} \rightarrow -d_{L,R}$
- There is a $s - b$ interchange symmetry: $s \leftrightarrow b$

The discrete symmetry involving the down quark is enforced to prevent $s \rightarrow d$ transition because of constraints from the kaon system. It also prevents $b \rightarrow d$ transitions since B_d mixing as well as the value of $\sin 2\beta$ measured in $B_d^0(t) \rightarrow J/\psi K_s$ are consistent with SM predictions. Although there may still be room for NP in $b \rightarrow d$ transitions, almost all deviations from the SM have been reported only in $b \rightarrow s$ transitions and so we assume no NP in $b \rightarrow d$ transitions in this work.

The above symmetries then give the following structure for the Yukawa matrices,

$$\begin{aligned} Y^D &= \begin{pmatrix} y_{11} & 0 & 0 \\ 0 & y_{22} & y_{23} \\ 0 & y_{23} & y_{22} \end{pmatrix}, \\ S^D &= \begin{pmatrix} s_{11} & 0 & 0 \\ 0 & s_{22} & s_{23} \\ 0 & s_{23} & s_{22} \end{pmatrix}. \end{aligned} \quad (5)$$

The diagonalizing of Y^D reduces S^D to a diagonal form also and so there are no FCNC effects associated with the second Higgs doublet. To introduce FCNC effects we introduce the strange quark mass as a small breaking of the $s - b$ symmetry and consider the structure,

$$Y_n^D = \begin{pmatrix} y_{11} & 0 & 0 \\ 0 & y_{22}(1+2z) & y_{22} \\ 0 & y_{22} & y_{22} \end{pmatrix}, \quad (6)$$

with $z \sim 2m_s/m_b$ being a small number.

At this point we can consider two scenarios: the first corresponds to the situation where the matrix S^D is still $s - b$ symmetric. This leads to an interesting prediction that there are no observable new weak phase in B_s mixing [15]. In the second case we will allow for small breaking of the $s - b$ symmetry in S^D in Eq. 5. This then results in an observable phase in B_s mixing. In this talk we will consider only the first scenario.

For the first case, S^D in the mass eigenstate basis has the form,

$$S^D \rightarrow S^{D'} = \begin{pmatrix} s_d e^{i\phi_{dd}} & 0 & 0 \\ 0 & s_s e^{i\phi_{ss}} & z s e^{i\phi_{sb}} \\ 0 & z s e^{i\phi_{sb}} & s_b e^{i\phi_{bb}} \end{pmatrix}, \quad (7)$$

where

$$\begin{aligned}
s_d e^{i\phi_{dd}} &= s_{11}, \\
s_s e^{i\phi_{ss}} &= (s_{22} - s_{23}), \\
s_b e^{i\phi_{bb}} &= (s_{22} + s_{23}), \\
s e^{i\phi_{sb}} &= s_{23}.
\end{aligned} \tag{8}$$

After integrating out the heavy Higgs bosons, $H^{1,2}$, which we shall henceforth rename S and P bosons, we can generate the following effective Hamiltonian for $\Delta B = 2$ and $\Delta B = 1$ processes,

$$H_{NP}^{\Delta B=2} = \frac{1}{2m_{S(P)}^2} z^2 s^2 \left[\pm e^{i2\phi_{sb}} O_{RR} \pm e^{-i2\phi_{sb}} O_{LL} + O_{RL} + O_{LR} \right], \tag{9}$$

with

$$\begin{aligned}
O_{LL} &= \bar{s}(1 - \gamma_5)b\bar{s}(1 - \gamma_5)b, \\
O_{LR} &= \bar{s}(1 - \gamma_5)b\bar{s}(1 + \gamma_5)b, \\
O_{RL} &= \bar{s}(1 + \gamma_5)b\bar{s}(1 - \gamma_5)b, \\
O_{RR} &= \bar{s}(1 + \gamma_5)b\bar{s}(1 + \gamma_5)b,
\end{aligned} \tag{10}$$

and

$$\begin{aligned}
H_{eff,NP}^{\Delta B=1} &= 4 \frac{G_F}{\sqrt{2}} z \frac{s s_q}{g^2} \frac{m_W^2}{m_{S(P)}^2} \left[\pm e^{i\phi_+} H_{RR} \pm e^{-i\phi_+} H_{LL} \right. \\
&\quad \left. + e^{i\phi_-} H_{RL} + e^{-i\phi_-} H_{LR} \right],
\end{aligned} \tag{11}$$

where the \pm sign is for S and P exchange interaction, $\phi_{\pm} = \phi_{sb} \pm \phi_{qq}$ and

$$\begin{aligned}
H_{LL} &= \bar{s}(1 - \gamma_5)b\bar{q}(1 - \gamma_5)q, \\
H_{RL} &= \bar{s}(1 + \gamma_5)b\bar{q}(1 - \gamma_5)q, \\
H_{LR} &= \bar{s}(1 - \gamma_5)b\bar{q}(1 + \gamma_5)q, \\
H_{RR} &= \bar{s}(1 + \gamma_5)b\bar{q}(1 + \gamma_5)q.
\end{aligned} \tag{12}$$

One can now study the predictions of this model for various FCNC processes involving the B meson. The structure of $H_{eff,NP}^{\Delta B=1}$ has just the right form found in Ref [13] to explain the various discrepancies in the rare B decays observed in experiments. In the next section we briefly discuss the predictions of the model.

3 Predictions and Conclusions

The predictions of our model are given below:

- As mentioned earlier, the effective $\sin 2\beta$ measured in pure penguin or penguin dominated $b \rightarrow s$ transitions are generally lower than that from $\sin 2\beta$ measured in $B_d^0 \rightarrow J/\psi K_s$. This is now a problem which is almost four years old and has not been resolved yet [16]. In our model the effective $\sin 2\beta$ measured in $b \rightarrow s$ transitions like $B_d^0(t) \rightarrow \phi K_s$, $B_d^0(t) \rightarrow \eta(\eta') K_s$, $B_d^0(t) \rightarrow K_s \pi^0$ etc are different and smaller than from $\sin 2\beta$ measured in $B_d^0 \rightarrow J/\psi K_s$. This is consistent with present experiments. Large branching ratios in charmless semi-inclusive $B \rightarrow \eta' X_s$ decays also have been difficult to understand in the SM [17] and it is plausible that our NP model may provide an explanation of this large branching ratio.
- The model gives a good fit to the data on the various $B_d^0 \rightarrow K\pi$ data [18].
- The model explains the large transverse polarizations observed in $B_d^0 \rightarrow \phi K^*$ and $B^+ \rightarrow K^{*0} \rho^+$ but not in $B^+ \rightarrow K^{*+} \rho^0$ [19]
- The predictions for B_s mixing [15] are consistent with experiments [20]. The phase in B_s mixing may or may not be observable even though new weak phases will be observable in hadronic $b \rightarrow s\bar{q}q$ transitions where $q = u, d, s$.

In conclusion, we expect NP to exist around a scale of TeV to stabilize the Higgs mass and provide an explanation for electroweak symmetry breaking. It is quite possible that this NP will contain new CP violating phases and since CP is not a symmetry of nature these CP odd phases can be large and hence detectable in rare B decays. Interestingly there are now several B decay modes in which there appear to be deviations from the SM predictions. These deviations could signal the presence of beyond the SM physics. In this work we were interested in a NP model that provides an explanation of all the deviations seen in several rare B decays. We considered a two Higgs doublet model with a 2-3 symmetry in the down type quark sector. The breaking of the 2-3 symmetry, introduced by the strange quark mass leads to FCNC in the quark sector that are suppressed by $\frac{m_s}{m_b}$ in addition to the mass of the heavy Higgs boson which is taken to be around a TeV . This model can explain all the deviations so far reported in several rare B decays and future precise measurements at B factories as well as results from upcoming collider experiments such as LHC will be able to test this model of new physics.

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